

Application for Letters Patent of

the UNITED STATES OF AMERICA by –

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Being a citizen of –

THE UNITED STATES OF AMERICA

For:

SOLID STATE TEMPERATURE MEASURING DEVICE AND METHOD

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5 **SOLID STATE TEMPERATURE MEASURING DEVICE AND
METHOD**

FIELD OF THE INVENTION

10 The present invention relates to a device and a method for measuring temperature, and more particularly to a device and method for digitally measuring an analog voltage, proportional to temperature.

BACKGROUND OF THE INVENTION

15 Numerous methods exist to measure temperature by using electronic devices such as semiconductors and resistors. Semiconductor devices used vary from a simple, low cost diode to a pair of transistors, specially manufactured for high temperature accuracy. Other devices use resistors of varying stability to support a highly accurate and easily calibrated temperature measuring device. The resistors are placed in a Wheatstone bridge configuration. A Wheatstone bridge is a common technique wherein a probe, typically a
20 thermistor, causes the bridge to become unbalanced as the temperature changes. The temperature changes sensed by the probe cause the bridge to transmit an analog signal.

 Temperature measurement is critical to many applications. Typically, a thermocouple device is insert into a liquid, gas, or in contact with a surface. As the
25 thermocouple senses a temperature change in its environment, the thermocouple circuit creates an analog signal. As opposed to a digital signal, or a series of zeros and ones that represent the state of an object, the analog signal is continuously variable with temperature. However, every analog signal must be converted to a digital signal for use by a computer system, such as a programmable logic controller (PLC) system.

30 A PLC control system has numerous inputs acting as conditions that a PLC acts upon. Based upon the input temperature, the control system may cause an alarm to sound, or slow the reaction rate through a reduction in a catalyst. It is the critical nature of temperature measurement across numerous applications that result in a wide variety of measuring devices.

5 A widely used temperature measurement device 100 in FIG. 1A uses a simple,
low cost diode in which a constant current I_A is applied from a current source. Every
diode 104 has a constant, called the Boltzman constant (K) and a junction voltage at the
base emitter 108 of the diode. This voltage shift with temperature is called the slope of
the diode, (S). The voltage 106 across the diode is proportional to the temperature based
10 upon the Boltzman constant and junction voltage change per a degree Celsius change, or
represented by the equation $T \approx K - S/\text{degree Celsius}$. The slope S and the Boltzman
constant K are measured in millivolts. In addition, each diode junction voltage 108 or
slope has an error term as the diode heats up because of the constant current source 102.

Other devices use a resistor circuit to adjust the slope of the diodes in the circuit.

15 These resistor circuits are used to compensate for the cold junction temperature of the
thermocouple. The cold junction or reference temperature is the analog output of the
thermocouple circuit at zero degrees Celsius. A thermocouple device produces an analog
output proportional to the measured temperature. Compensating for the cold junction
temperature improves the accuracy of the thermocouple device. The analog-to-digital
20 converter reads the voltage difference between the measured temperature and the cold
junction temperature. A fixed cold junction signal produces an accurate and repeatable
base signal to the analog-to-digital converter. A similar system is described in U.S. Pat.
No. 4,441,071, which is incorporated herein by reference. In another system, amplifiers
and a power supply are added to the resistor network to compensate for the cold junction
25 temperature. A similar system is described in U.S. Pat. No. 4,126,042, which is
incorporated herein by reference.

Other devices use a combination of resistors and amplifiers to measure a voltage
change, hence, a temperature change over a predefined range. Typically, these systems
are used for measuring high temperatures requiring a highly accurate result. The
30 temperature represented by the output signal is low to moderate requiring the use of
amplifiers. A similar system is described in U.S. Pat. No. 5,611,624, which is
incorporated herein by reference.

Yet in other devices, the resistor not the diode provides the analog signal based
upon the sensed temperature change. The resistors are configured in a Wheatstone bridge
35 circuit with a power source applied across the circuit. A first circuit called a reference

5 circuit provides a first signal that is constant to the analog-to-digital converter. A second
circuit called a bridge circuit provides a second signal, the second signal's output is
proportional to the temperature change, to the analog-to-digital converter. The
comparison of the two separate signals allows the use of inexpensive resistors in the
circuit to achieve a highly accurate temperature measurement. A similar system is
10 described in U.S. Pat. No. 5,655,305, which is incorporated herein by reference

FIG. 1B shows a specially manufactured transistor circuit 150 for measuring
temperature. This circuit 150 improves measuring accuracy at a much greater cost than
the single diode device 100 of FIG. 1A. A pair of transistors 158 and 160, having a
known surface area ratio, are inputs to a differential amplifier 166. A voltage 152 is
15 applied across the transistors 158, 160 and a pair a resistors 154, 156 to draw currents 162
and 164 through the transistors. The ratio of the surface areas of the transistor pair 158
and 160 yields a known slope. The error term of the junction voltage at the base emitter
cancels out when the current density or surface area of each transistor is controlled at the
time of manufacture. The slope, S , of each transistor is known after manufacture.

20 The voltage change due to the measured temperature causes the currents 162 and
164 to flow through the transistor pair 158, 160, which amplify the small voltage change.
The amplified voltage across the transistor pair 158, 160 is the input to a differential
amplifier 166, having an output proportional to the absolute temperature measured
(PTAT). One of the transistors 158, 160 in the transistor pair is the cold junction or
25 reference temperature circuit. A similar system is described in the National
Semiconductor LM34, LM82, LM83, and LM84 specifications, which are incorporated
herein by reference. A similar system is described in U.S. patent No. 4,475,103, which is
incorporated herein by reference.

Although some devices use a diode or a group of diodes, each temperature device
30 design trades cost for accuracy and temperature range. The temperature device of FIG.
1A has the advantage of low cost and an output signal capable of being measured without
additional circuitry. Additional circuitry increases manufacturing cost, thus, an increased
cost to the end product. Moreover, additional circuitry increases cost because of
engineering and design considerations in the product using the more complicated circuit.

5 The diode circuit of FIG. 1A has many disadvantages shared by other low cost
circuits. The temperature range and accuracy depends upon the diode type and details of
its manufacture. The design engineer using the device of FIG. 1A must have engineering
information on the diode itself. Regardless of the diode, the circuit of FIG. 1A has an
inherently low accuracy and requires calibration before use. Calibration fixes the use of
10 the FIG. 1A circuit, thus, limiting its reuse in other applications. Last, the higher the
temperature measured the lower the voltage output from the circuit. This would require
additional circuitry thus leading to an increased cost.

 The cold junction or reference temperature circuit of other devices leads to
additional cost and engineering complexity. Without a cold junction temperature, the
15 actual measurement has no baseline. Additional circuitry provides a cold junction analog
signal as an input to the circuitry of the temperature measuring device. The additional
circuitry narrows the use of the temperature measuring devices. The narrowed use results
from a need to improve accuracy and reduce the calibration time. Electronic circuits lose
accuracy because of the heat generated from current used to power the circuit itself. To
20 compensate for lost accuracy, the circuit designers tend to use more expensive electronic
components and design for narrower temperature ranges. Designing for narrower
temperature ranges allows one to apply the electronic circuit accurately to the narrower
range, resulting in a higher resolution much like microscope at high power. The
additional circuitry has more stable resistors, power amplifiers, and specially
25 manufactured transistors.

 The circuit of FIG. 1B uses a pair of transistors. This circuit has a much higher
cost, almost sixty times the circuit of FIG. 1A because of the engineering and
manufacturing in the diodes contained in the transistors and the circuit supporting the
matched diode pair. Like the diodes of FIG. 1A, the user must know the diode type and
30 the details of its manufacture.

 The temperature circuit of FIG. 1B has better accuracy than FIG. 1A and a wider
temperature range than FIG. 1A. However, the circuit of FIG. 1B requires careful
matching of the diodes at manufacture. In addition, more circuitry is required to measure
the analog signal proportional to the temperature measured.

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SUMMARY OF THE INVENTION

The present invention provides a method and system for automated temperature measurement. The system, on which the method is based, includes a programmable logic controller, a temperature measurement diode, an analog-to-digital converter coupled to the diode and the programmable logic controller, a current source coupled to the diode and configured to generate a first current and a second current different from said first current, and a processor coupled to the current source and to the analog-to-digital converter. The processor controls the current source such that the current source sequentially applies the first current to the diode at a first point in time and applies the second current to the diode at a second point in time. The processor also receives a first voltage across the diode measured when the first current is applied to the diode and a second voltage across the diode measured when the second current is applied to the diode. Based on the first and second voltages, the processor determines the temperature proximate the diode.

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BRIEF DESCRIPTION OF THE DRAWINGS

A more complete appreciation of the invention and many of the attendant advantages thereof will be readily obtained as the same becomes better understood by reference to the following detailed description when considered in connection with the accompanying drawings, wherein:

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FIG. 1A is an illustration of a single diode circuit having a constant current and a measurement of a voltage proportional to the temperature of the system controlled.

FIG. 1B is an illustration of a dual transistor circuit having constant current source passed through a pair of matched transistors with a known ratio between transistor junction areas;

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FIG. 2A is an exemplary system employing several variations of the temperature measurement device of the present invention;

FIG. 2B is a conceptual illustration of the temperature measurement device of one embodiment of the present invention;

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FIG. 3A is a schematic illustration of one embodiment of the temperature measurement device of the present invention;

5 FIG. 3B is an illustration of an I/O module employing the temperature measurement device of the present invention;

 FIG. 4 is a flowchart explaining how the present invention calibrates the temperature measuring device in accordance with an embodiment of the present invention; and

10 FIG. 5 is a flowchart explaining how the present invention measures temperature, according to one embodiment;

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to the drawings, wherein like reference numerals designate
15 identical or corresponding parts throughout the several views, and more particularly to FIG. 2A thereof, there is shown a conceptual diagram of an exemplary programmable logic controller (PLC) system of the present invention. PLC 214a, temperature units 300c and 300d, and I/O module 216e communicate over network 204b, and PLC 214b, 214c, I/O modules 216a and 216b, and temperature units 3001 and 300b communicate over
20 network 204a.

Networks 204a and 204b may be Ethernet networks or any other suitable bus, LAN, backplane or other hardware and/or software that permits various devices to communicate. Networks 204a and 204b may form all or part of a larger network, such as the Internet 208, which enables components of network 204a to communicate with
25 components of network 204b.

PLCs 214a, 214b, 214c are programmable and may or may not include I/O modules 216 configured according to the present invention. For example, PLC 214b has no I/O module, whereas PLCs 214a and 214c include I/O modules 216d and 216c, respectively. Typically, PLCs are used in factory automation to control various factory
30 processes, such as temperature measurement.

I/O modules 216a, 216b, 216c, 216d, and 216e are hardware for sending and receiving data. In particular, the I/O modules 216 of FIG. 2A deliver commands to the temperature units 300a, 300b, and 300c to cause the temperature units 300 to calibrate and to measure temperature. The I/O modules 216 also receive temperature measurement
35 information from the temperature units 300. I/O modules 216 may be implemented as

5 cards that are inserted into a PLC (such as I/O modules 216c and 216d) or as hardware that is connected to the same backplane or network as the PLCs 214 and the temperature units 300.

The temperature units or measuring devices 300a, 300b, 300c, and 300d are calibrate and measure temperature of any surface to which they are thermally coupled.

10 The temperature units 300 may be connected to one or more of the PLCs 214 in the system in any number of ways. For example, temperature unit 300a is connected directly to I/O device 216b, temperature units 300b and 300c are connected directly to networks 204a and 204b, respectively, and temperature unit 300d is connected directly to PLC 214a (e.g., via the I/O module 216d). The temperature units 300 communicate status
15 information and temperature measurements to one or more of the PLCs 214 via I/O modules 216.

Figure 2B conceptually shows how temperature measurements are made according to one embodiment of the invention. A PLC 214 sends a command to a temperature unit 300 to begin calibration and/or temperature measurement. These
20 commands can be sent over network 204, over the Internet 218, directly (e.g., PLC 214a sends a command directly to I/O module 216d), and/or via an I/O module. For example, PLC 214a may send a command to temperature unit 300a via the Internet 208, and I/O module 216b.

In FIG. 2B commands 217 from PLC 214 are relayed by I/O module 216 to a
25 controlled current source 224 coupled to, or forming a part of, temperature unit 300. For example, I/O card 216d within PLC 214a signals controlled current source 224 associated with temperature unit 300b). Command 217 causes the controlled current source 224 to apply a first current to temperature unit 300. A voltage measurement 226 takes place in the temperature unit 300, resulting in an analog signal 228 that represents the voltage.
30 Analog-to-digital (A/D) conversion 230 converts the analog signal 228 into a digital signal representative of the voltage. This digital signal is stored in temperature unit 300. Shortly after the first command 217, PLC 214 sends a read command 220 via I/O module 216 to read the digital voltage measurement stored in an A/D converter of the temperature unit 300. After the read command 220, the A/D converter writes the
35 converted voltage measurement 226 to a digital signal 222 to the PLC 214.

5 Once the PLC 214 retains a valid measure, a second command 217 instructs the controlled current source 224 to change the current by a fixed multiple of the original current. Preferably, the current source 224 changes the current by a fixed integral amount. Then the process repeats itself by performing a voltage measurement 226, A/D conversion 230, and sending a second digitized voltage measurement to PLC 214.

10 Once the two voltage values are read by PLC 214, PLC 214 calibrates the temperature measuring system 232 using the Ideal Diode Equation. The Ideal Diode Equation measures temperature in degrees Kelvin as proportional to the change in voltage. The Ideal Diode Equation is given by $\Delta V_{BE} = V_{BE1} - V_{BE2} = \eta kT/q \ln(J_{E1}/J_{E2})$. V_{BE1} is the first voltage measurement and V_{BE2} is the second voltage measurement. Most
15 designs use two diodes, which require the current density (J) of each diode as a variable in the Ideal Diode Equation. K is the Boltzman constant and q is the charge on the electron. Both K and q are known and fixed, unlike the current density of the diodes. No two diodes are manufactured alike and each has inaccuracies as given by η . In the present invention, both η and the current density's J_{E1} and J_{E2} when the same diode 308
20 is used.

FIG. 3A is a schematic diagram of a solid state temperature unit or measuring device 300, according to an embodiment of the invention. Control signals 302 control the operation of a power supply 303 and an analog-to-digital converter 310 (shown by dashed lines).

25 Processor 312 is any controller, CPU, circuit, or logic device for sending control signals 302 to power source 303 and A/D converter 310. The processor 312 generates control signals to cause the power supply 303 to generate currents that are applied to a diode 308. A/D converter 310 reads the analog diode voltage as currents are applied to the diode 308 from the power supply 303. The analog-to-digital converter 310 converts
30 the analog diode voltages to digital form and sends the digital voltages to the processor 312, which uses the diode voltages to determine the temperature of a surface onto which the diode 308 is mounted. The processor 312 generates control signals 302 to control when the analog-to-digital converter 310 reads the diode voltages and sends the digitized diode voltages to the processor 312. It is to be understood that processor 312 does not
35 form a portion of the temperature unit 300 in some embodiments. In those embodiments,

5 the processor 312 is located in PLC 214 or any other suitable device in communication with the temperature unit 300. In other embodiments, processor 312 forms a portion of, and is integral with, temperature unit 300.

Power supply 303 may be either a single current source for providing different currents to the diode 308. If power supply 303 supplied to different currents to the diode
10 308 at different times, then the power supply 303 may be conceptually represented by two current sources 304 and 306, as shown in FIG. 3. However, power supply 303 may also be implemented as two separate current sources, which alternately supply a current to the diode 308 under the control of the control signals 302 received from the processor 312. The diode 308 is preferably a semiconductor diode but may be any other device
15 over which voltage measurements may be taken to derive temperature. The analog-to-digital converter 310 is preferably a 16-bit high precision analog-to-digital converter. However, any other type of analog-to-digital converter may be used, depending on the degree of precision desired in the measurement of the voltage across the diode 308.

The processor 312 is any commercially available central processing unit for
20 controlling the application of currents by the power source 303 and the read in and read out of voltages by the analog-to-digital converter. Additionally, the processor 312 uses the digitized voltages received from the analog-to-digital converter 310 to calculate the temperature of the surface onto which the diode 308 is mounted. It is to be understood that any processor or multiple processors may be used to perform the functionality of the
25 processor 312. For example, a micro controller or a simple timing and arithmetic unit may be used in place of the processor 312. Further, part of the functionality of the processor 312 may be divided over one or more local processors and one or more processors that are remote from the diode 308. For example, the timing of the current supplied from the power supply 303 and the reading and output of voltages by the
30 analog-to-digital converter 310 may be controlled by a processor remotely located in a PLC system and/or across a local area network (LAN) or wide area network (WAN), such as the Internet 218.

Figure 3B is a schematic illustration of an I/O module 216 with an integrated temperature unit 300. Thus, in Figure 2A, any of the I/O modules 216 may include
35 temperature units 300. However, it is not necessary that the I/O modules 216 include

5 temperature units 300 as any of the I/O modules may be connected to one or more temperature units 300 directly or via a network. The present invention includes the processes and functions performed by the processor 312. FIGS. 4 and 5 are flowcharts for explaining the operation of the temperature unit 300, processor 312, power supply 303, analog-to-digital converter 310, and other components of the system shown in
10 Figure 2A. In step 400, the processor 312 initiates or receives a command to start calibration of the temperature unit 300. In step 402, the processor 312 outputs a control signal 302, causing power supply 303 to apply a first current 306 to the diode 308. Alternatively, the power supply 303 supplies the first current 306 to the diode 308 in a default mode so that no control from the processor 312 is required in order for the first
15 current I_1 to be applied.

In step 404 the processor 312 sends a control signal 302 to the analog-to-digital converter 310, causing the analog-to-digital converter 310 to measure the voltage drop across the diode 308 at a point in time while the first current is supplied to the diode 308. Alternatively, logic circuitry may be used to cause the analog-to-digital converter to
20 periodically measure the voltage across the diode 308 whenever the first current is supplied to the diode 308 by the power supply 303. In this embodiment as well as others, it may be advantageous to integrate the processor 312 and the A/D converter 310.

In step 406 the analog-to-digital converter 310 converts the measured analog voltage to digital format and the digitized result is stored in memory, such as a register or
25 cache in the analog-to-digital converter 310 or the processor 312. Alternatively, the digitized voltage measurement may be stored in a random access memory (RAM) coupled to the processor 312 or may be stored in a cache or register of the processor 312. Once the digitized voltage measurement is stored, the analog-to-digital converter sends to the processor 312 a signal indicating that the first voltage measurement has been taken
30 and digitized.

In step 408 the processor 312 generates a control signal 302 causing the power supply 303 to apply a second current, different from the first current, to the diode 308. Preferably, the first current and the second current are fixed and known, and the second current is a multiple, n , of the first current. For example, the multiple n may be equal to

5 1/2, 1/3, 1/4, 2, or 3. The generation of the second current may be controlled in alternate ways, as explained above with respect to the first current.

 In step 410 the processor 312 sends a control signal 302 to the analog-to-digital converter 310, causing the analog-to-digital converter to measure the diode voltage or voltage drop across the diode 308 at a point in time while second current is applied to the diode 308. Voltage measurement in step 410 may be performed in alternate ways as
10 described above with respect to step 404.

 Upon completion of the second voltage measurement, in step 412 the analog-to-digital converter 310 converts the measured analog voltage to digital format and the digitized result is stored in memory. Once the second digital voltage measurement is
15 stored, the analog-to-digital converter 310 sends to the processor 312 a signal indicating that the second voltage measurement has been taken and digitized. A/D conversion and storage may be performed in alternate ways, including those described above with respect to step 406.

 In step 414 the processor 312 reads the first and second voltages out of the
20 analog-to-digital converter and calculates the temperature of the surface to which the diode 308 is mounted, using the Ideal Diode Equation. This step provides the differential voltage proportional-to-absolute temperature (PTAT).

 FIG. 5 is a flowchart explaining in greater detail how the present invention determines the temperature of the surface or body to which the diode 308 is mounted and/or proximate, based on the Ideal Diode Equation. Temperature measurement is
25 nearly identical conceptually to temperature calibration, so the processes described with respect to FIGs. 4 and 5 are largely interchangeable. In this particular embodiment, the A/D converter 310 includes circuitry for measuring and storing voltage measurements as well as for subtracting the first voltage and the second voltage.

30 In step 502 the processor 312 causes the current source to apply the first current to the diode 308 and causes the A/D converter 310 to measure and store the voltage across the diode 308. In step 504 the processor 312 causes the current source to apply the second current to the diode 308 and causes the A/D converter 310 to measure and store the voltage across the diode 308. In step 506 the processor 312 subtracts the voltage
35 resulting from the higher current from the voltage resulting from the lower current. Thus,

5 if the second current is greater than the first current, then the second voltage is subtracted from the first voltage. In step 508, the difference between the first and second voltages, obtained in step 506, is digitized by the analog to digital converter.

Then, in step 509 the digitized difference in the voltages is transmitted to the processor 312. In step 510, the temperature of the mass or body proximate the diode is
10 determined by the processor by multiplying the difference between the voltages by a constant, using the Ideal Diode Equation. This constant is the ratio of the Boltzman constant, k , and the charge on the electron, q . The resulting product is the temperature of the surface to which the diode 308 is mounted in degrees Kelvin.

The temperature calculated in step 510 is output to different devices, depending
15 on the particular use of the temperature unit 300. For example, in one embodiment the temperature is supplied to a thermocouple module and the temperatures supplies the cold junction reference used to measure temperature at a remote end of the thermocouple. In other embodiments, the temperature may be sent to PLC 214 or other factory automation control device, such as a monitor or a memory that includes a database of temperature
20 measurements over time.

As explained above, the temperature system and method of the present invention has a single diode having a first end operably connected to a pair of current sources, and having a second end connect to ground. The single diode is in thermal communication with a heat conducting surface. At the start-up of a system in which the device resides, a
25 microprocessor starts the calibration cycle. The microprocessor turns on the current sources. This starts a first current to flow through the diode circuit. Shortly thereafter, the microprocessor signals an analog-to-digital converter to read the voltage drop across the diode. The analog-to-digital converter reads the voltage and converts the analog signal to a digital signal. The microprocessor reads the digital signal and stores the value
30 in a first temporary memory.

Next, the microprocessor via a control circuit changes to a second current. Shortly, thereafter the microprocessor signals an analog-to-digital converter to read the voltage drop across the diode. The analog-to-digital converter reads the voltage and converts the analog signal to a digital signal. The microprocessor reads the digital signal
35 and stores the value in a second temporary memory. The microprocessor via the control

5 circuit maintains a constant ratio between the two current flows. Maintaining a known ratio of currents, the common terms cancel out leaving only the actual variables to be measured.

Having the analog voltage signal of both current flows converted to a digital value, the microprocessor determines the PTAT of the diode circuit. Using the ideal
10 diode equation, the microprocessor determines the slope, S , and with the Boltzman constant, K , of the diode itself the output voltage proportional to the actual temperature measured can be determined during operation of a PLC system.

The present invention removes the inherent diode error terms. The error term cancels out when the same diode is used. Moreover, an inexpensive diode can be used
15 rather than a specially manufactured transistor and its associated circuitry. In typical PLC system, the system already contains a microprocessor, the PLC itself. Also, an analog-to-digital converter resides in a typical PLC system to convert other analog signals to digital signals for use by the microprocessor.

Additionally, embodiments of the present invention are able measure temperature
20 over a wide range with an accuracy of $+ \text{ or } -1$ degree Celsius accuracy at room temperature. The device is simple to recalibrate, if needed, and can be reused. The present invention does not require complicated circuitry or expensive components. The device needs a current control circuit and diode, as the microprocessor and analog-to-digital converter already exists in a typically PLC system. The device is compact and
25 small. The device can be placed most anywhere on a thermal surface in the PLC system. Last, the control circuit can be integrated into the control logic of the PLC itself. The PLC system having the microprocessor can interrupt or make contact with the control circuit at anytime during its program logic to measure the actual temperature. The diode circuit during operation is constantly transmitting an output voltage proportional to the
30 temperature. The constant output signal is an input into the analog-to-digital converter. The PLC instructs the control circuit to read the input signal, convert and transfer into a first temporary PLC memory location the temperature measured. Moreover, the PLC system can be programmed to recalibrate based on a counter that performs the calibration, as described above, after a preset number of actual temperature
35 measurements. This automatic recalibrate ensures accurate temperature measurement for

5 critical applications. In addition, the PLC can store the calibration data and temperature readings for historical and quality control reporting purposes.

Obviously, numerous modifications and variations of the present invention are possible in light of the above teachings. It is therefore to be understood that within the scope of the appended claims, the invention may be practiced otherwise than as
10 specifically described herein.